SINGLE-PARTICLE BEAM DYNAMICS IN BOOMERANG*

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Abstract

We describe simulations of the beam dynamics in the storage ring (Boomerang), a 3-GeV third-generation light source being designed for the Australian Synchrotron Project[1]. The simulations were performed with the code Goemon[2]. They form the basis for design specifications for storage ring components (apertures, alignment tolerances, magnet quality, etc.), and for determining performance characteristics such as coupling and beam lifetime.

INTRODUCTION

"Boomerang" is the 3-GeV storage ring at the heart of the Australian Synchrotron Project (ASP), a National facility being built by the Victorian Government at a site adjacent to Monash University, 20 km from the center of Melbourne. Like other modern intermediate energy facilities, Boomerang features auxiliary sextupoles in the dispersion-free region of the lattice (sometimes called harmonic sextupoles) in order to provide an acceptable dynamic aperture. In this case the dynamic aperture was found to lie well outside the anticipated physical aperture. This then gives us the opportunity to match various physical parameters (apertures, RF voltage, etc.), whilst maintaining overall performance requirements such as beam lifetime. In this paper we describe the lattice and basic beam dynamics of the storage ring, and the process through which the physical parameters of the accelerator components are defined.

THE MAGNET LATTICE AND BEAMDYNAMICS

The magnet lattice [3] has been optimized to emphasize a low beam emittance within a short achromatic section. One unit cell of the lattice is shown schematically in Fig. 1, and the lattice functions are plotted in Fig. 2 for the nominal, and Fig.3 for the low-emittance mode operations. Notable in the design are: (1) the chromatic sextupoles SV and SH are "embedded" in the compound achromat magnets - thereby minimizing the strengths of the sextupoles; and (2) there are no defocusing quadrupoles in the long straight section - giving more space for straight section elements. The periodicity of the lattice is 14 resulting in a circumference of 216 m. Beam parameters are summarized in Table 1.

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With this magnet configuration the auxiliary sextupoles were optimized to give adequate dynamic aperture. The resulting dynamic aperture (see Fig. 4 for the nominal mode) is insensitive to the absolute setting of the sextupoles to about 10% of their setting. I.e., these settings do not represent a narrow peak of the maximum aperture in auxiliary sextupole space. It has also been found that the dynamic aperture is not sensitive to magnet errors (in normal ranges), since the amplitude dependent tune variations are small until the test particles get close to the edges of the dynamic aperture. As an example, we show ν_x as a function of betatron amplitude in Fig. 5 for the nominal mode. Again this seems typical of lattices designed with auxiliary sextupoles.

Table 1. Main Beam parameters

Energy	3.00		GeV
Circumference	216.006		m
Beam Current	200		mA
νx	13.3		
νy	5.2		
βx*	9.47	8.23	m
βy*	2.46	2.43	m
η*	0.00	0.247	m
Mom.Compaction	1.97E-3	2.09E-3	
Natural Chrom H	-30.8	-28.5	
Natural Chrom V	-23.9	-24.4	
Radiation Loss	931.6		keV/turn
Natural E Spread	1.02E-3	1.03E-3	
Natural Emittance	1.58E-8	6.97E-9	
Rad. Damping H	3.42	3.38	msec
Rad. Damping V	4.64	4.64	msec
Rad. Damping E	2.82	2.86	msec
k of Bend	-0.335		1/m^2
k of Q1	1.7617	1.7891	1/m^2
k of Q2	-0.9145	-0.9174	1/m^2
k of Q3	1.9244	1.9064	1/m^2
RF Frequency	499.654		MHz

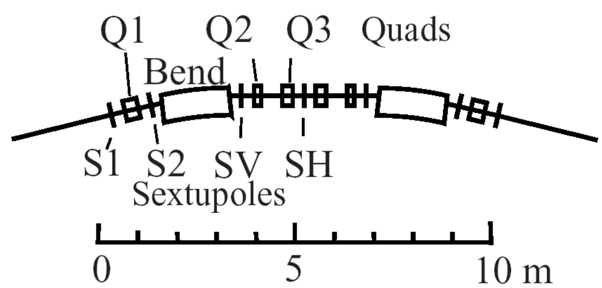

Figure 1. Unit Cell

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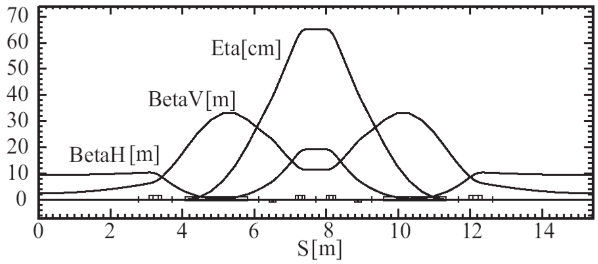

Figure 2. Nominal Mode Lattice Function

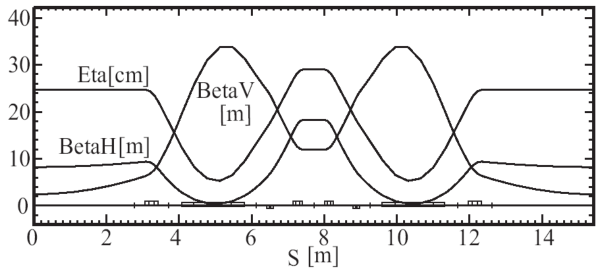

Figure 3. Low-Emittance Mode Lattice Function

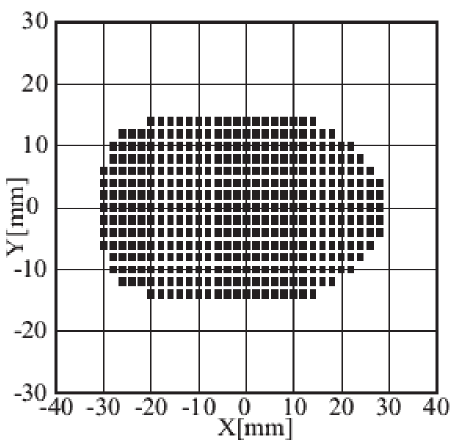

Figure 4. Dynamic Aperture for 400 Turns

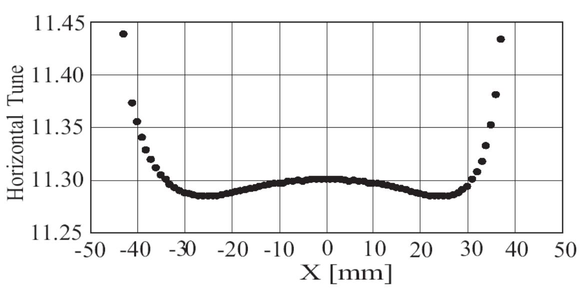

Figure 5. Amplitude-dependent Tune Shift Horizontal

APERTURE

Given that the storage ring has a dynamic aperture that is likely to be larger than the physical apertures in the storage ring, we are free to define accelerator apertures and magnet good-field regions through other constraints.

Vertical beam stay-clear

We choose to define the vertical stay-clear by a 4 m long vacuum chamber centered in the long straight section, with an aperture of +/- 5 mm. Under almost all reasonable scenarios for βy* this defines the aperture to be constrained to a value of 5 mm at by = 4.0 m, or alternatively the vertical acceptance is defined to be Ay = 6.25 x 10^{-6} m-rad. The maximum vertical beam stay-clear occurs in the dipole magnets at a value of +/- 15 mm. The dipole magnets must be designed with an aperture consistent with this.

Horizontal stay-clear

The horizontal stay-clear in Boomerang turns out to be dominated by the apertures required to contain Touschek scattered electrons. We will show later that this aperture gives a horizontal acceptance that is much larger than the vertical acceptance. This in turn means that elastic gas scattering lifetimes are limited by just one plane – the vertical plane.
The bremsstrahlung lifetime in Boomerang is about 40 hours. In order to get a Touschek lifetime of ~ 40 hours we need an RF voltage of 3 MV. Such a voltage, at 500 MHz, can be achieved by four warm cavities, or possibly by a single superconducting cavity. This is equivalent to an energy acceptance of ~ 2.2%. Note that this is also well within the dynamic energy acceptance of the ring, which is in excess of 4%.

Tracking Touschek 2.2% scattered particles around the ring show that they paint an aperture that reaches 33 mm in the center of the achromat. Fig. 6 shows the trajectories around the ring of a -2% scattered particle over 100 turns.

We therefore choose the horizontal stay clear consistent with the above argument. In the straight sections it corresponds to a value of 14 mm, and the maximum quadrupole and sextupole apertures must be consistent with a good field region of +/- 33 mm in the center of the achromat. We note that the horizontal acceptance is Ax > 23 x 10^{-6} m-rad (defined by the position of the injection septum), and that this is significantly larger than the vertical acceptance.

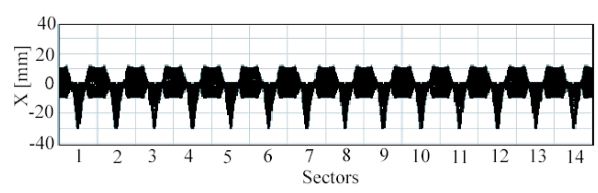

Fig.6 Overlapping Trajectories of a Particle Scattered with -2 % of Energy Deviation

BEAM LIFETIME

We are now in a position to estimate beam lifetimes.
We make the following assumptions:
(1) Use the apertures and RF voltages described above.
(2) Vacuum pressure of 1 nTorr, N_2 equivalent.
(3) Beam current of 200 mA in 300 bunches out of 360 buckets.
(4) Emittances per Table 1; i.e. 16 and 7 nm-rad.
We then get values of:

Table 2: Components of the Beam Lifetime

Emittance	**16 nm**	**7 nm**
Coulomb scattering	78 hours	77 hours
Bremsstrahlung	39 hours	39 hours
Touschek	102 hours	39 hours
Quantum	huge	huge
Combined	20.7 hours	15.6 hours

INSERSION DEVICE COMPENSATION SCHEME

The four families of sextupole magnets work very effectively to increase the dynamic aperture. Therefore, the ring is quite tolerant to the effect of insertion devices. An extreme scenario for simulation is to insert two ALS W16 wigglers (λw = 16 cm, 19 periods, B_{max} = 2.1 T) in consecutive sectors. The resulting β-beat is ~ 15 %. Such beating can be corrected locally by using quadrupoles on each side of the wiggler. The global tunes are refitted. The loss of the dynamic aperture is up to 10% after re-optimizing the sextupoles. For undulators, compensation using 6 quadrupoles on both sides of each undulator is sufficient.

LATTICE ERRORS AND ORBIT CORRECTIONS

The closed orbit distortion (COD) is very sensitive to lattice errors, and precise COD correction is required to restore the machine performance. There are 70 horizontal correctors, 56 vertical correctors and 98 beam position monitors for the COD correction. The COD was simulated with the random magnet errors listed in Table 3 and corrected by using the singular-value decomposition (SVD) method based on the sensitivity matrices.

Table 3: Magnet Random Errors

Field Error $\Delta K/K$	1.0E-3
Tilt Error ΔT	0.5E-3 rad
Misalignment	0.15E-3 m

The residual COD rms average over tens of random seeds is 0.16~0.18 mm in both transverse planes with the BPM readout error of 0.15 mm. If the target values are given to the BPM readout, it goes down to ~ 0.05 mm by using the ideal sensitivity matrices.

In reality, once the beam is stored with reasonable beam time, it becomes possible to use beam-based alignment and analysis. Note that in Boomerang all quadrupoles are powered separately. We estimate that the residual COD with respect to these quadrupole centers will be 0.01~0.02 mm by taking advantage of measured sensitivity matrices.

The higher-order field errors of the magnets have also simulated to confirm that they do not hamper the COD correction or the resulting dynamic aperture. After correction, the loss of the dynamic aperture is estimated at 10 ~ 15 % of the ideal. The average corrector setting is around 0.1 mrad in both planes

DISCUSSION

The design of a light source is an iterative process in which one desired parameter can be traded off against others, including the cost of the facility. We have shown above that in the case of the ASP we have arrived at a reasonably self-consistent set of parameters. Given the lattice, which itself was the result of many iterations between circumference, number of achromats, emittance, and overall size, etc., we have a solution in which:

- the dynamic aperture in all three planes is outside the apertures defined by physical constraints;
- the cavity voltage is reasonable (more would require more cavities, larger-aperture multipole magnets, and less would reduce the beam lifetime);
- the beam stay-clear is reasonable (larger would require larger-aperture multipole magnets, and less would reduce the beam lifetime);
- the magnet apertures and vacuum requirements are consistent with recognized norms within the synchrotron community; and
- the beam lifetime is acceptable.

REFERENCES

[1] http://www.synchrotron.vic.gov.au/
[2] H. Nishimura, “Goemon, A C++ Library for Accelerator Modeling and Analysis,” PAC 2001, Chicago, July 2001, p. 3066.
[3] J.W. Boldeman, “The Australian Synchrotron Light Source”, EPAC 2002, Paris, June 2002, p. 650.